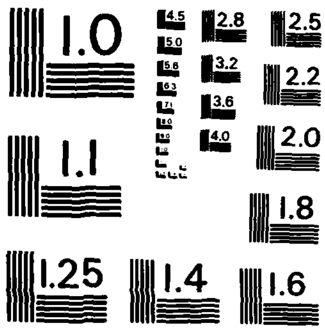
AD-A121 696 ON THE EXTRAPOLATION OF SPACE-SIMULATION BEAM-PLASMA INVESTIGATIONS TO SH..(U) NAVAL RESEARCH LAB WASHINGTON DC E P SZUSZCZEWICZ 09 NOV 82 NRL-MR-4941 1/1

UNCLASSIFIED SBI-AD-E000 507 F/G 20/9 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

NRL Memorandum Report 4941

On the Extrapolation of Space-Simulation Beam-Plasma Investigations to Shuttle-Borne Applications

E. P. SZUSZCZEWICZ

E. O. Hulburt Center for Space Research
Space Science Division

November 9, 1982

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 4941	2. GOVT ACCESSION NO. AD-A121 696	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ON THE EXTRAPOLATION OF SPACE-SIMULATION BEAM-PLASMA INVESTIGATIONS TO SHUTTLE-BORNE APPLICATIONS		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) E. P. Szuszczewicz		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N; RR033-02-44; 41-0949-02
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, VA 22217		12. REPORT DATE November 9, 1982 13. NUMBER OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Laboratory-based space-simulations
Beam-plasma parameters
Beam-plasma-discharge (BPD)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Laboratory simulations of space-plasma phenomena provide an important link in establishing broader perspectives of various plasma processes, in helping to understand spatially- or temporally-limited rocket and satellite observations, and in planning future spaceborne experiments. One such area has been the artificial injection of energetic electron beams in space which has transitioned from an early and somewhat confused set of rocket data, through a relatively intensive program of laboratory-based space-simulations, to an ambitious program which exploits the Shuttle as a readily-accessible laboratory in space. While accumulated information points to a considerably improved understanding (Continues)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

of beam-plasma parameters which define single-particle behavior on the one hand and collective beam-plasma properties on the other, the extrapolation of these results to Shuttle-borne applications is met with a number of constraints. Focusing on the transition from single-particle behavior to the collective nonlinear interactions in the beam-plasma-discharge, this paper provides a comparative analysis on aspects involving Shuttle-unique environmental effects. Emphasis is placed on Shuttle potentials and associated sheaths, ambient plasma and neutral density effects including relative spacecraft motion, pulsed versus dc gun operation, and beam-plasma-discharge criteria in general. The laboratory-based space-plasma simulations are found to provide valuable guidelines for intelligent planning of Shuttle-based beam-plasma investigations and promote a productive era of plasma experiments in space.

CONTENTS

I. INTRODUCTION 1

II. SHUTTLE-BORNE APPLICATIONS 4

- Plasma Sheaths 6
- Ignition of the BPD 9
- Existence of a Pre-Beam Plasma 11
- Pulsed Gun Operation 12

III. COMMENTS AND CONCLUSIONS 14

ACKNOWLEDGEMENTS 15

REFERENCES 16

Nomenclature

B	magnetic field
c	velocity of light
e	electron charge
I_c	critical beam current for BPD ignition
k	Boltzmann constant
L	beam-plasma system length
m_e	electron mass
N_b	energetic electron beam density
N_e	ambient plasma density
N_n	ambient neutral density
P	neutral gas pressure
R_p	probe (or Shuttle) radius
R_s	sheath radius
S	dimensionless sheath size
T_e	electron temperature
V_b	energetic electron beam accelerating potential
θ	beam injection angle
λ_D	Debye length, $(kT_e/4\pi N_e e^2)^{½}$
ϕ_p	probe (or Shuttle) potential
$\omega_c^e\ 2\pi$	electron cyclotron frequency, $eB/2\pi m_e c$
$\omega_D/2\pi$	electron drift frequency, $kT_e(dN_e/dx)/eB\lambda N_e$
$\omega_p^e\ 2\pi$	electron plasma frequency, $(N_e e^2/\pi m_e)^{½}$

ON THE EXTRAPOLATION OF SPACE-SIMULATION BEAM-PLASMA INVESTIGATIONS TO SHUTTLE-BORNE APPLICATIONS

I. INTRODUCTION

The artificial injection of energetic particle beams in space represents one of the most exciting areas for controlled experiments in the Earth's ionosphere and magnetosphere[1,2]. Under the influence of a large number of controlling parameters[3] (e.g., N_b, N_e, V_b, B, N_n and θ), a monognergetic electron beam can follow well-defined single-particle trajectories or it can undergo collective beam-plasma effects that destroy the simple single-particle description and render the beam-plasma system unstable to a multitude of plasma modes[4]. If the beam behaves as a single-particle model would predict, there are a number of valuable spaceborne applications that include the mapping of geomagnetic field lines, detection of geomagnetic conjugates, the study of beam-spreading, atmospheric excitation and ionization processes, and the measurement of magnetic-field-aligned potentials. On the other hand, there is great interest in studying the collective beam-plasma processes that destroy the "classical" single-particle behavior. This interest focuses on basic beam-plasma interaction processes and their relationships to a variety of space-plasma phenomena including:

(a) non-linear ionization,

(b) wave-particle interactions,

(c) plasma turbulence and anomolous diffusion in high latitudinal ionospheric domains,

(d) the generation of electrostatic and electromagnetic waves, and

(e) anomolous spacecraft charging/discharging mechanisms in energetic particle environments.

Manuscript approved September 8, 1982.

In recent years, one of the subjects in space-related beam-plasma interactions to receive considerable attention has been the collective plasma process called the beam-plasma-discharge (BPD)...a phenomenon related to each of the issues listed above as items (a) through (e). Fundamentally, an hf discharge triggered by nonlinear interactions between the beam and ambient plasma electrons, the BPD was first studied in the 1963 laboratory work of Getty and Smullin[5]. It began to gain the attention of the space science community when the initial series of spaceborne beam experiments in 1970 yielded results that were at substantial variance with expectations[6-8]. Further rocket experiments[9-12] and rather intensive laboratory simulations,[13-20] supported by theoretical analyses,[18,21-22] provided many clues to the previously ill-understood spaceborne results. Today, a fair amount is known about the BPD characteristics and the nonlinear processes that drive the basic hf beam-plasma interactions. It is generally agreed that the BPD is a complex beam-plasma state that is triggered at a critical beam current with a parametric dependence[3] on the beam energy, the superimposed magnetic field, the ambient neutral density and system length. This critical current level yields:

(i) a marked increase in ion-pair production (factors up to 20 times greater than that which would result from single-particle collisional ionization processes);

(ii) a greatly enhanced 3914Å emission;

(iii) a broadening of the beam-plasma cross-section (a factor of 10 is typical) and an associated modification of the primary beam velocity distribution;

(iv) the creation of a large suprathermal electron population extending over the 5-100 eV range;

(v) the generation of intense hf emissions to frequencies above the electron plasma frequency ω_p^e; and

(vi) the development of large amplitude (up to an order of magnitude), low frequency ($\lesssim$ 150 Hz) ion acoustic and/or drift-wave modes.

Since many of these results are steady-state BPD signatures and have found plausible theoretical descriptions, it is fair to say that the steady-state space-simulated BPD is approaching a reasonable level of accepted scientific understanding. However, the extrapolation of this understanding to spaceborne applications is accompanied by a number of conditions which have not been adequately simulated nor extensively studied. These conditions include the existence of a uniform and quiescent pre-beam plasma, the existence of a moving beam-plasma reference frame (as would be the case for a Shuttleborne accelerator), an unbounded beam length, manifestations of plasma density turbulence, temporal beam-plasma behavior and possible spacecraft perturbations involving plasma sheaths and gaseous effluents.

These items come as no surprise to workers in the field and indeed several of the issues have had limited treatment[23-24]. The existence of a uniform and quiescent pre-beam plasma is an important consideration since progressive applications of beams in space will initially concentrate on stable and homogeneous regions of the ionosphere. In contrast, the pre-BPD plasma in the large-chamber space simulations (and undoubtedly in the original gas discharge work) is far from quiescent. Indeed, the study of charged-particle-beam interactions with turbulent plasmas is a subject in its own right. In some cases, the presence of plasma inhomogeneities (or turbulence) can attenuate an instability process while in other cases the same inhomogeneities may lead to new instabilities.

It is clear that each of the issues require substantial consideration before extrapolations can be made from the space-simulation results to Shuttle-borne applications. With this perspective, subsequent sections will describe planned Shuttle experiments, measurement requirements and potential impact of Shuttle-unique environmental constraints.

II. SHUTTLE-BORNE APPLICATIONS

As noted above, the extrapolation of laboratory space-simulation results to Shuttle-borne applications is met with a number of qualifications. These qualifications can be put into perspective with reference to Figure 1 which schematically displays various beam-plasma interaction domains in Shuttle-borne applications. (See References 25-27 for more detailed discussions of beam-injection considerations on the Shuttle.) The NASA/Spacelab Program plans a number of Shuttle-borne beam-plasma investigations, incorporating the Japanese SEPAC experiment[25] (SEPAC = Space Experiments with Particle Accelerators). SEPAC subsystems include an electron beam accelerator which can deliver currents and beam energies up to 1.5 amps and 7.5 keV in a pulse-controlled mode. Pulse widths are variable from 10 ms to 1 sec at repetition rates ranging from 0.1-60s^{-1}. (NASA also plans a number of studies employing a faster but lower power electron gun (1 keV, 100 ma) which is part of an experimental effort called VCAP[28], Vehicle Charging And Potential. (The first VCAP tests were conducted on STS-3.) When an electron beam is injected into the ionosphere, interaction processes can be cataloged into four space-time regions[26,27], labelled I through IV in Figure 1. The study of these four regions is the subject of a NASA-supported program TEBPP[26,27] (Theoretical and Experimental Study of Beam-Plasma-Physics).

In Region I, the beam is expected to spread as a result of various effects which include its own space charge repulsion, neutralization by ambient and beam-created plasma, and beam divergence. In addition, Region I is considered to include the effects of spacecraft charging and potentially large plasma sheaths which will alter the beam energy by an amount equal to the potential drop across the sheath.

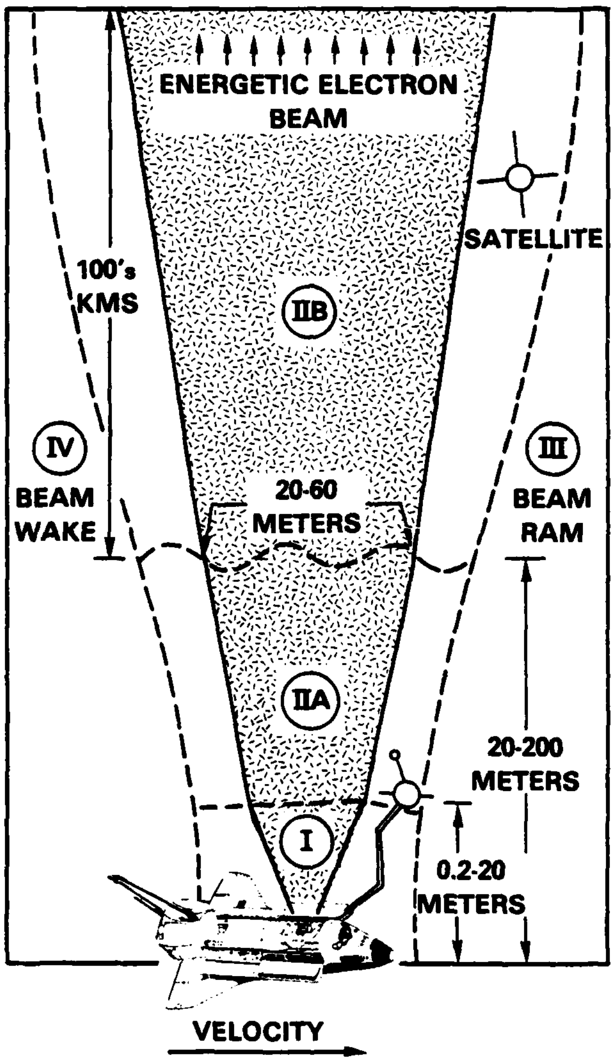


Fig. 1 — Schematic representation of beam-plasma interaction domains in Shuttle-borne applications[26,27]

Region II-A defines the region in which the beam has reached an equilibrium condition (from a geometrical perspective), and begins strong beam-plasma interaction processes that spread the beam energy distribution function, develop strong AC electric fields and result in various forms of plasma turbulence. If BPD is to occur in planned Shuttle experiments, it is expected to occur in this domain.

The beam, with its modified energy distribution function, then moves into the kinetic regime (Region II-B) where the AC electric fields are expected to be considerably less than in II-A.

Region III is ahead of the beam where precursor effects are likely to be detected; and IV is in the beam wake where the ionosphere returns to its original unperturbed state.

It is planned that these regions will be probed by complementary instrument packages...one mounted on the end of the Shuttle's 15 meter Remote Manipulator System (RMS) and one on a maneuverable sub-satellite. The degree to which beam-plasma processes can be properly diagnosed in Shuttle-borne applications and the degree to which laboratory-based simulations can be applied to mission planning will now be addressed in a number of select areas.

Plasma Sheaths

It is an established fact that the operation of energetic particle accelerators on space vehicles can have significant effects on the vehicle potential and the attendant plasma sheath. Because of plasma current conservation laws, it is possible in tenuous plasma environments for the spacecraft to charge to positive potentials equal in magnitude to the beam energy. These potentials are expected to result in anomalously large plasma sheaths.

Extrapolation of existing probe theory can establish an estimate of possible sheath sizes. Consider[29]

$$S = (R_s - R_p)/\lambda_D = [2.50 - 1.54 \exp(-0.32\, R_p/\lambda_D)](e\phi_p/kT_e)^{1/2} \quad (1)$$

where S is the dimensionless sheath thickness for a positively charged cylindrical body of radius R_p immersed in a fully-Maxwellian, magnetically-free plasma at rest. λ_D is the electron Debye length and $e\phi_p/kT_e$ is the body (vehicle) potential normalized to the ambient electron temperature. Taking the thick- and thin-sheath limits we find

$$\lim_{R_p/\lambda_D \to o} (S) = (e\phi_p/kT_e)^{\frac{1}{2}} \tag{2a}$$

and

$$\lim_{R_p/\lambda_D \to \infty} (S) = 2.5\ (e\phi_p/kT_e)^{\frac{1}{2}}, \tag{2b}$$

respectively. Since R_p (the Shuttle radius in our case) will tend to be large compared with λ_D, equation (2b) more appropriately represents the experimental configuration. Substituting $e\phi_p/kT_e$ = 1, 10, 10^2, 10^3 and 10^4 yields the results summarized in TABLE I.

The sheath sizes listed in Table I suggest that for operation near peak ionospheric densities ($N_e \sim 10^6 cm^{-3}$) Shuttle sheaths should not be much of a problem, even if the spacecraft charges to 1300 volts. At low ambient densities ($N_e \sim 10^3 cm^{-3}$) sheath sizes can become comparable to RMS (<u>R</u>emote <u>M</u>anipulator <u>S</u>ystem) dimensions (6.7 meter sheath at 130 volts, 21 meter sheath at 1300 volts). Under these conditions, it is unlikely that any instrumented package mounted at the end of the RMS will penetrate regions of the Shuttle-near-space unperturbed by sheath potentials.

It should be pointed out that equation (1) cannot be applied rigorously to the full domain of possible sheath sizes and Shuttle potentials. Attendant limitations are identified with the assumptions in the physical model employed in the derivation. Ramming currents, magnetic field effects, secondary electron sputtering, surface conductivities,

Table I — Sheath Sizes

	Reasonable Limits of Probe Theory			Substantial Extrapolations of Model		Plasma Conditions	
$e\phi/KT_e$	1	10	10^2	10^3	10^4	$N_e(cm^{-3})$	$T_e(^oK)$
$S=(R_s-R_p)/\lambda_D$	2.5	7.9	25	79	250	-	-
(R_s-R_p) meters	0.21	0.67	2.1	6.7	21	10^3	1500
(R_s-R_p) meters	0.007	0.021	0.07	0.21	0.70	10^6	1500
ϕ_p (volts)	.13	1.3	13	130	1300	-	1500

detailed Shuttle geometry and ionization sources within the sheath have all been neglected. Because of the complexity of the problem and inherent assumptions that are necessitated (even if all effects are included), it is unlikely that a more complicated model will yield improved confidence in final predictions.

<u>Ignition of the BPD</u>

The possibility of BPD ignition in Shuttle applications can be viewed from a number of perspectives. We focus here on ignition criteria established in space-simulation laboratory experiments. These criteria are summarized in Figures 2 and 3. and associated equations 3 and 4, respectively.

$$I_c(A) = 6.0(10^{11})\left\{\frac{(V_b[\text{Volts}])^{3/2}}{(B[\text{gauss}])^{0.7}\ P[\text{Torr}]L[\text{m}]}\right\} \tag{3}$$

$$\overline{\omega_p^e} = 5.4\ \omega_c^e \tag{4}$$

With regard to Figure 2 we emphasize considerations regarding pressure. In the case of the other parameters note that $0.2 \lesssim B(\text{gauss}) \lesssim 0.6$ for nominal Shuttle orbits and that the system length L is not expected to be a controlling term. L dependence in equation (3) is interpreted in two ways: (i) ion loss rates to the ends of the chamber, and (ii) resonance feedback for finite system size resulting in an absolute instability under space-simulation conditions. In the unbounded Shuttle application the instability is expected to be convective and therefore carries no L-dependence. In addition, there are considered to be no unit volume loss rates along the unbounded system axis and if BPD were ignited for a 20 meter length in laboratory simulation, it is expected to be ignited in space[30] (all other parameters being the same).

Typically, Shuttle altitudes will be confined to domains between 200 and 400 km where diurnal and solar-cycle variations

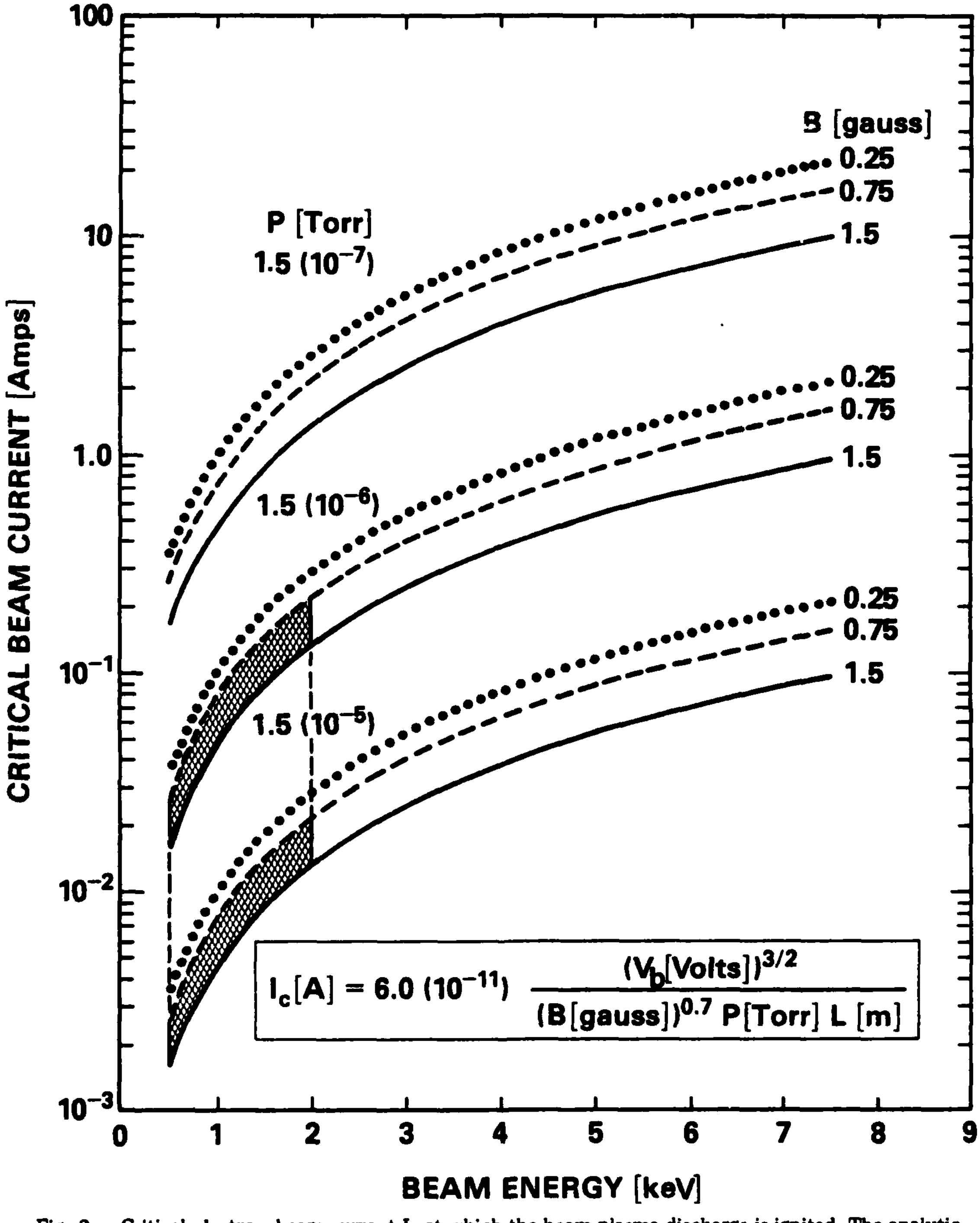


Fig. 2 — Critical electron beam current I_c at which the beam-plasma-discharge is ignited. The analytic representation is an empirical fit to the original laboratory results of Bernstein et al[14] for parallel injection. The connected cross-hatched region represents the parametric domain over which the original experiments were conducted. For comparative purposes note that the Shuttle-borne SEPAC accelerator has I(max), V_b(max) = 1.5 A, 7.5 keV.

allow $9(10^{-8}) \lesssim P(\text{torr}) \lesssim 3(10^{-7})$ at the lowest altitude limit and $3(10^{-9}) \lesssim P(\text{torr}) \lesssim 2(10^{-8})$ at the upper altitude region. Reference to Figure 2 suggests that BPD ignition at 400 km ($\langle P \rangle \sim 1(10^{-8})$) is a virtual impossibility with the SEPAC accelerator ($I(\max)$, $V_b(\max)$ = 1.5A, 7.5 keV). At the very lowest altitude ($\langle P \rangle \sim 2(10^{-7})$) BPD ignition appears possible only for maximum SEPAC current (1.5 amps) at energies less than 1.5 keV. However, SEPAC gun perveance appears to preclude BPD operation in this domain.

The results of Figure 2 also suggest that the VCAP electron gun at (0.1A, 1.0 keV) is marginally-capable of triggering BPD in the low altitude regime. Local increases in pressure (e.g., factors of only 2-5) due to Shuttle outgassing will greatly increase VCAP BPD-ignition probabilities.

It is important to note that this discussion of pressure limitations on BPD ignition is greatly simplified in that it has not included the motion of the beam across the geomagnetic field. This motion can represent a loss mechanism as the beam moves away from field lines where it has already created ionization. Considerations of this phenomenon suggest that even at 200 km altitudes the SEPAC accelerator will not be able to trigger BPD if the only neutrals available for ionization are from the natural environment. However, the SEPAC experiment includes a nitrogen source for creation of a <u>n</u>eutral <u>g</u>as <u>p</u>lume (NGP). The NGP has been designed to provide neutral densities in the range 10^{12}-10^{13} cm^{-3}, corresponding to pressures of the order 10^{-5} torr. Except for the NGP nozzle velocity this plume will move along with the Shuttle and make the SEPAC ignition of BPD a virtual certainty.

<u>Existence of a Pre-Beam Plasma</u>

While the critical current relationship (equation (3)) established the controlling system parameters for BPD ignition in the laboratory-simulations, a more fundamental form of the ignition criterion involved a plasma density dependence. Early thoughts[5,14] suggested that $\omega_p^e \gtrsim \omega_c^e$ satisfied ignition threshold criteria while a recent systematic direct measurements effort[18] yielded $\omega_p^e = 5.4\ \omega_c^e$ as the plasma density dependent form of BPD threshold conditions (see Fig. 3). The majority of these BPD experiments were conducted without a pre-existing plasma, that is, the beam interacted with the plasma which it created in collisions with ambient neutrals. In ionospheric applications, there will be a naturally-occurring plasma environment with a density which varies with magnetic latitude, altitude, and local solar zenith angle as well as solar and geomagnetic activity. For most considerations the ambient plasma densities at Shuttle altitudes will vary from a maximum value near $2(10^6)\ cm^{-3}$ to a minimum $\sim 10^4 cm^{-3}$. The upper limit is a harder number than the lower since orbital passes below the F-region peak and through the mid-latitude trough could push the lower limit to $\sim 10^3 cm^{-3}$. Recalling that $0.2 \lesssim B(\text{gauss}) \lesssim 0.6$ at Shuttle altitudes, Figure 3 suggests that the density-dependent threshold criterion[18] $\omega_p^e \gtrsim \omega_e^c$ can be readily satisfied in Shuttle beam-plasma applications. The question to be answered however is whether or not the ω_p^e/ω_c^e criterion applies to the situation in which there exists a pre-beam plasma. Theoretical models suggest it does but the exact value is dependent upon gun geometry and beam-expansion processes. In any event, it is expected that the condition $\omega_p^e/\omega_c^e \gtrsim 1$ will apply but an exact value ($\omega_p^e/\omega_c^e = 5.4$?) remains to be determined.

Pulsed Gun Operation

The operation of the gun with pulse widths as short as 10 ms is expected to lead to varying results. This is illustrated in Figure 4 where the temporal behavior of relative plasma density is presented for three consecutive electron gun pulses under laboratory conditions. The gun's current and voltage were set for BPD conditions at 34 ma and

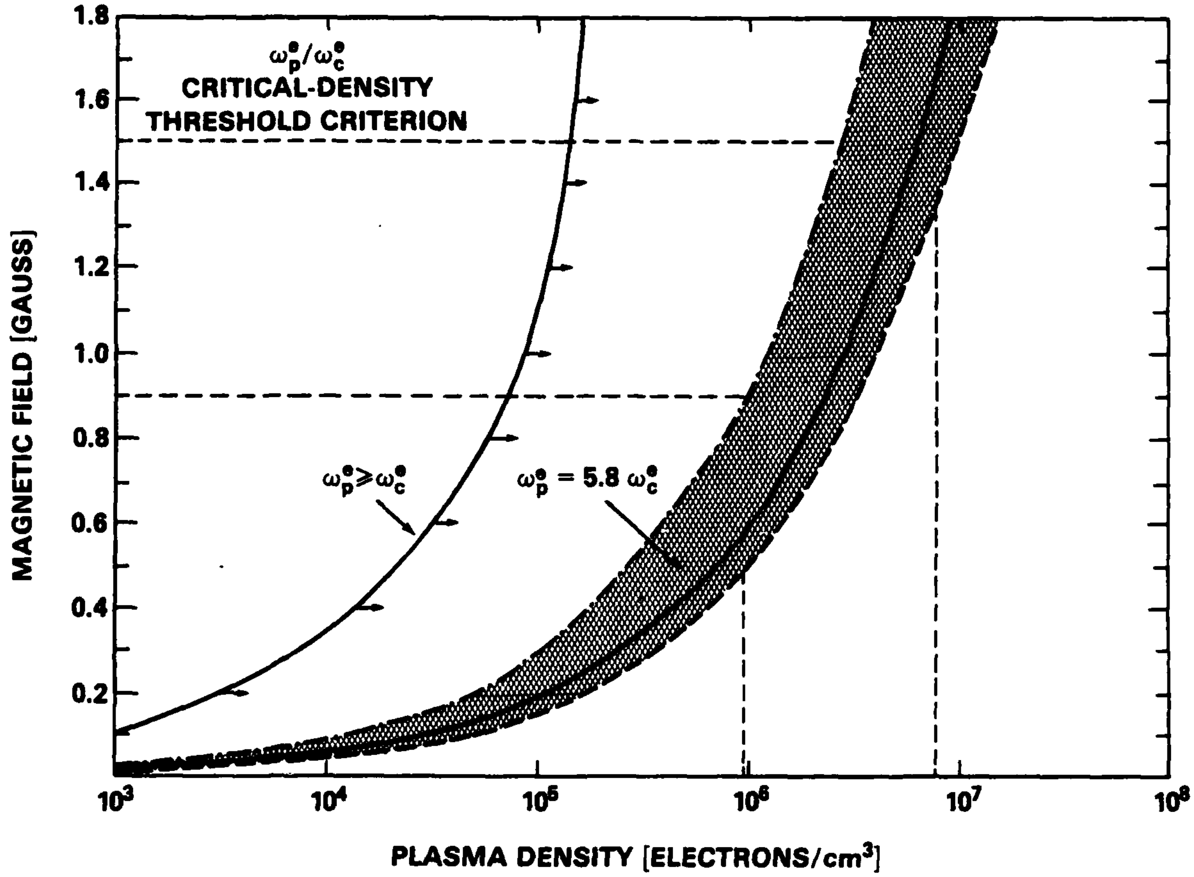


Fig. 3 — Density-dependent ignition criterion for BPD ignition. $\omega_p^e/\omega_c^e = 5.4$ was the average value determined experimentally. The dotted lines identify range of experimental parameters while the crosshatched region represents spread in the results. The condition $\omega_p^e \geq \omega_c^e$ stems from earlier investigations[5,14].

1.9 keV, respectively, and the pulse operation cycle was at 80 msec ON and 270 msec OFF for a total 350 msec period. The results in the figure can be characterized as follows:

(i) A rapid increase in plasma density as the gun turns on (about 3 orders of magnitude increase in approximately 5 msec);

(ii) A "flat" quasi-steady-state BPD condition during the pulse-ON time; and finally

(iii) An exponential decay in plasma density once the gun pulse is terminated.

Two points will be made relative to the results in Figure 4:

(a) The BPD onset time is a function of gun current (previously treated in Ref. 18), energy, and ON/OFF cycle time. If the pulse width had been less than 5 msec for the conditions in Figure 4, BPD would not have been achieved.

(b) The onset time dependence on ON/OFF cycle time represents a dependence on the local plasma density when the gun is retriggered. For shorter OFF times (and correspondingly higher local pre-beam plasma densities) the onset time is reduced. This means that BPD onset time in a pre-beam plasma environment is shorter than cases in which the beam itself generates the plasma. Thus, the presence of ionospheric plasma may help alleviate possible problems of plasma loss as the beam moves across the geomagnetic field.

III. COMMENTS AND CONCLUSIONS

The conditions detailed in the preceding paragraphs by no means exhaust the various issues to be considered in extrapolating the current understanding of beam-plasma interactions to Shuttle-borne applications (see e.g., Ref. 23). It cannot be emphasized too strongly that such extrapolations must be recognized for what they are...indicators of possible effects and guidelines for experiment planning. Even within the areas treated the approach has been somewhat cursory with a focus on primary impact rather than comprehensive treatment.

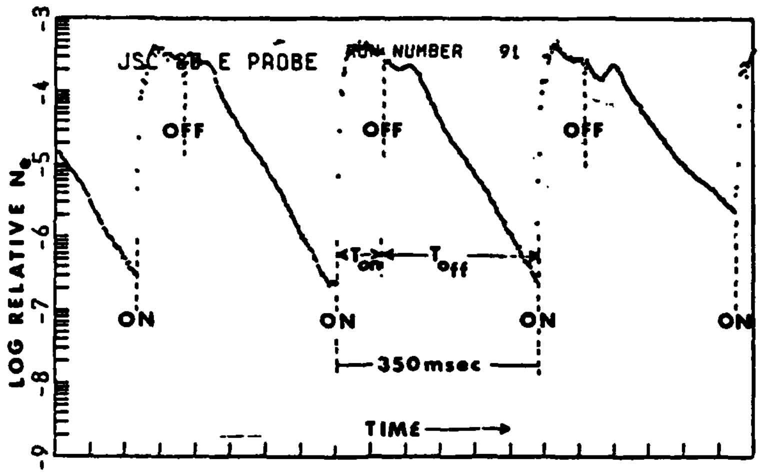


Fig. 4 — Time-dependent plasma response during three consecutive pulsed-gun periods. $N_e^{max} = (1.3 \pm 0.5)\,(10^7)\ cm^{-3}$.

Limitations notwithstanding, it is expected that accumulated rocket-borne and laboratory information along with intelligent instrument design and experiment planning will lead to successful energetic electron beam experiments on Shuttle... experiments that reap the benefits of single particle behavior as well as those which explore the multitude of nonlinear interactive processes in beam-plasma systems.

ACKNOWLEDGEMENT

It is with great pleasure that the contributions and discussions of the entire TEBPP Science Team be acknowledged. Valuable inputs have been provided by H. Anderson, W. Bernstein, K. Papadopoulos, H. Leinbach, P. Kellogg, J.C. Holmes, D.N. Walker, T. Hallinan, J.R. Jost, L. Linson, R. Holtzworth and P. Rodriguez.

REFERENCES

1. Winkler, J.R., "The Application of Artificial Electron Beams to Magnetospheric Research", Rev. Geophys. and Space Phys. 18, 1980, pp. 659.

2. Grandal, B., editor, Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982.

3. Szuszczewicz, E.P., "Laboratory Simulations of Controlled Energetic Electron-Beam-Plasma Interactions in Space", AIAA J. (1982, in press).

4. Linson, L.M., and K. Papadopoulos, "Review of the Status of Theory and Experiment for Injection of Energetic Beams in Space", Report No. LAPS 69 SAI-023-80-459-LJ, Science Applications Inc., La Jolla, CA (1980).

5. Getty, W.D., and L.D. Smullin, "Beam Plasma Discharge: Buildup of Oscillations", J. Appl. Phys. 34, 1963, pp. 3421.

6. Hess, W.N., M.C. Trichel, T.N. Davis, W.C. Beggs, G.E. Kraft, E. Stassinopoulos, and E.J.R. Maier, "Artificial Aurora Experiment: Experiment and Principal Results", J. Geophys. Res. 76, 1971, pp. 6067.

7. Hendrickson, R.A., R.W. McEntire, and J.R. Winckler, "Electron Echo Experiment: A New Magnetospheric Probe", Nature Vol. 230, No. 5296, pp. 564-566, 1971.

8. Cartwright, D.G., and P.J. Kellogg, "Observations of Radiation from an Electron Beam Artificially Injected into the Ionosphere", J. Geophys. Res. 79, 1974, pp. 1439.

9. Cambou, F., V.S. Dokoukine, V.N. Ivchenko, G.G. Mangadze, V.V. Migulin, O.K. Nazarenko, A.T. Nesmyanovich, A.K. Pyatsi, R.Z. Sagdeev, and I.A. Zhulin, "The Zarnitza Rocket Experiment on Electron Injection", Space. Research XV, 1975, pp. 491.

10. Cambou, F., J. Lavergnat, V.V. Migulin, A.I. Morozov, B.E. Paton, R. Pellat, A. Kh. Pyatsi, H. Rème, R.Z. Sagdeev, W.R. Sheldon, and I.A. Zhulin, "ARAKS-Controlled or Puzzling Experiment?" Nature 271, 1978, pp. 723.

11. O'Neil, R.R., F. Bien, D. Burt, J.A. Sandock, and A.T. Stair, Jr., "Summarized Results of the Artificial Auroral Experiment, Precede", J. Geophys. Res. 83, 1978, pp. 3273.

12. Galeev, A.A., E.V. Mishin, R.Z. Sagdeev, V.D. Shapiro, and I.V. Shevchenko, "Discharge in the Region Around a Rocket Following Injection of Electron Beams into the Ionosphere", Sov. Phys. Dokl. (English Translation) 21, 1976, pp. 641.

13. Bernstein, W., H. Leinbach, P. Kellogg, S. Monson, T. Hallinan, O.K. Garriott, A. Konradi, J. McCoy, P. Daly, B. Baker, and H.R. Anderson, "Electron Beam Injection Experiments: The Beam-Plasma Discharge at Low Pressures and Magnetic Field Strengths," Geophys. Res. Lett., 5, 1978, pp. 127.

14. Bernstein, W., H. Leinbach, P.J. Kellogg, S. J. Monson, and T. Hallinan, "Further Laboratory Measurements of the Beam-Plasma-Discharge", J. Geophys. Res. 84, 1979, pp. 7271.

15. Smullin, L., D., "A Review of the Beam-Plasma Discharge", in Relation Between Laboratory and Space Plasmas, Hiroshi Kikuchi, editor, D. Reidel Publishing Co., (Dordrecht/Boston/London). 1981, pp. 4566.

16. Anderson, H.R., R.J. Jost, and J. Gordenk, "Electron Energy Distribution Produced by Beam-Plasma-Discharge", NATO Advanced Research Institute, Geilo, Norway, April 1981, see also Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982, pp. 351.

17. Jost, R.J., H.R. Anderson, and W. Bernstein, "Radial Dependence of the HF Wave Field-Strength in the BPD Column", NATO Advanced Research Institute, Geilo, Norway, April 1981, see also Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982, pp. 431.

18. Szuszczewicz, E.P., K. Papadopoulos, W. Bernstein, C.S. Lin, D.N. Walker, "Threshold Criteria for a Space Simulation Beam-Plasma Discharge", J. Geophys. Res. 87, 1982, pp. 1565.

19. Szuszczewicz, E.P., D.N. Walker, J.C Holmes, and H. Leinbach, "Plasma Diffusion in a Space Simulation Beam-Plasma-Discharge," Geophys. Res. Lett. 6, 1979, pp. 201.

20. Kellogg, P.J., H.R. Anderson, W. Bernstein, T. J. Hallinan, R.H. Holzworth, R.J. Jost, H. Leinbach and E.P. Szuszczewicz, "Laboratory Simulation of Injection of Particle Beams in the Ionosphere", NATO Advanced Research Institute, Geilo, Norway, April 1981, see also Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982, pp. 289.

21. Rowland, H.L., C.L. Chang, and K. Papadopoulos, "Scaling of the Beam-Plasma-Discharge", J. Geophys. Res. 86, 1981, pp. 9215.

22. Papadopoulos, K., "Theory of Beam-Plasma Discharge", NATO Advanced Research Institute, Geilo, Norway, April 1981, see also Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982, pp. 505.

23. Linson, L.M., and K. Papadopoulos, "Theoretical Support of the Spacelab Instrument/Experiment Definition of a Theoretical and Experimental Study of Beam-Plasma Physics (TEBPP)", Report No. LAPS 76/SAI-023-081-316-LJ, Science Applications Inc., La Jolla, CA (Sept. 1981).

24. Szuszczewicz, E.P., C.S. Lin, "Time-Dependent Plasma Behavior Triggered by a Pulsed Electron Gun Under Conditions of Beam-Plasma-Discharge", NATO Advanced Research Institute, Geilo, Norway, April 1981, see also Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982, pp. 361.

25. Obayashi, T., "Space Experiments with Particle Accelerators: SEPAC Program for the First Spacelab Mission", in Relation between Laboratory and Space Plasmas, Heroshi Kikuchi, editor D. Reidel Publishing Co. (Dordrecht/Boston/London), 1981, pp. 299.

26. Anderson, H.R., W. Bernstein, H. Leinbach, K. Papadopoulos, L.M. Linson, E.P. Szuszczewicz, T. Hallinan, and P.J. Kellogg, "Theoretical and Experimental Study of Beam-Plasma-Physics using Shuttle/Spacelab for the Experiments", Dept. of Space Physics and Astronomy, Rice University, NASA Proposal, November 1978.

27. Anderson, H.R., and W. Bernstein, "Theoretical and Experimental Beam-Plasma-Physics (TEBPP): Summary of Definition Study for Requirements Review", Science Applications Inc., Bellevue, Wash., September 1981.

28. Banks, P.M., W.J. Raitt, and W.F. Denig, "Studies of Beam-Plasma Interactions in a Space Simulation Chamber using Prototype Space-Shuttle Instruments", NATO Advanced Research Institute, Geilo, Norway, April 1981, see also Artificial Particle Beams in Space Plasma Physics, Plenum Publishing Co., New York, 1982, pp. 393.

29. Szuszczewicz, E.P., and P.Z. Takacs, "Magnetosheath Effects on Cylindrical Langmuir Probes", Phys. Fluids 22, 1979, pp. 2424.

30. Linson, L., and K. Papadopoulos, private communication, 1981.